

# The Faint Young Sun Paradox: An Observational Test of an Alternative Solar Model

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**Abstract.** We report the results of deep radio observations (3.6 cm) of the nearby solar-type star  $\pi^{01}$  Ursa Majoris with the Very Large Array (VLA) intended to test an alternative theory of solar luminosity evolution. The standard model predicts a solar luminosity only 75% of the present value and surface temperatures below freezing on Earth and Mars at 4 Ga, seemingly in conflict with geologic evidence for liquid water on these planets. An alternative model invokes a compensatory mass loss through a declining solar wind that results in a more consistent early luminosity. The free-free emission from an enhanced wind around nearby young Sun-like stars should be detectable at microwave frequencies. Our observations of  $\pi^{01}$  UMa, a 300 million year-old solar-mass star, place an upper limit on the mass loss rate of  $4-5 \times 10^{-11} \text{ M}_{\odot} \text{ yr}^{-1}$ . Total mass loss from such a star over 4 Gyr would be less than 6%. If this star is indeed an analog of the early Sun, it casts doubt on the alternative model as a solution to the faint young Sun paradox, particularly for Mars.

## Introduction

The paradox of the faint young Sun is one of the outstanding problems in understanding the early climates of the Earth and Mars. Standard stellar evolution theory predicts that the solar luminosity at the beginning of the Archean eon (3.8 Ga) was approximately 75% of its present value [Gough, 1981]. The lower insolation at the distances of Earth and Mars should have resulted in surface temperatures below 0°C, in apparent conflict with geological records which suggest warmer temperatures and liquid water at the surface of both worlds [Sagan and Mullen 1972; Karhu and Epstein, 1986]. Elevated levels of CO<sub>2</sub>, a greenhouse gas, may have maintained surface temperatures above freezing on the early Earth and Mars [Owen *et al.*,

1979; Cess *et al.*, 1980; Walker *et al.*, 1981; Kasting and Grinspoon, 1991]. Carbonates from a massive carbon dioxide greenhouse have yet to be discovered on Mars, and the CO<sub>2</sub> levels postulated for the Archean Earth may be in conflict with the geochemical record [Rye *et al.*, 1995]. This has led to theories involving methane (CH<sub>4</sub>) and ammonia (NH<sub>3</sub>) as greenhouse gases [Kasting, 1997; Sagan and Chyba 1997].

An alternative model of solar evolution, originally constructed to explain the anomalous depletion of lithium in the Sun (and similar stars) has the potential to resolve the paradox [Hobbs *et al.*, 1989; Schramm *et al.*, 1990]. The model invokes mass loss of  $\sim 5\text{--}10\%$  over the age of the Sun to remove its outermost, Li-rich layers [Boothroyd *et al.*, 1991]. The luminosity of a star on the main sequence scales with its mass as a power-law with index 3-4. Thus, a small amount of mass loss could compensate for much of a star's luminosity evolution due to the thermonuclear consumption of hydrogen [Graedel *et al.*, 1991]. Conservation of angular momentum would impel the expansion of planetary orbits, moderating the *flux* at a planet to an even greater degree [Whitmire *et al.*, 1995]. To explain warm Archean conditions, the mass loss must occur over a timescale of  $\sim 1$  Gyr. The mass loss rate must also be  $\sim 10^{-11} - 10^{-10} M_{\odot} \text{ yr}^{-1}$ , three to four orders of magnitude higher than the present solar wind. Agreement between solar oscillation frequencies and the standard solar model may limit mass loss to the first 0.2 Gyr of solar history, an uninteresting timescale in this context [Guzik and Cox, 1995]. Evolution in solar wind intensity would be a natural consequence of the decline in solar chromospheric activity over 4.6 Gyr [Walter and Barry, 1991; Stauffer and Soderblom, 1991], but the magnitude of the change is unknown. A much stronger early wind would by itself have profound consequences for the erosion of the terrestrial planet atmospheres [Kass and Yung, 1995].

The qualitative record of ion implantation record in meteorites and lunar samples suggests a more intense ancient wind [Geiss and Bochsler, 1991] but does not extend beyond 0.1 Gyr. Observations of young, solar-type stars can be used to test the plausibility of significant early solar mass loss. Detection of mass loss would imply similar behavior by the early Sun. Likewise, restrictive upper limits on the rate of mass loss from these stars would cast doubt on the theory. Stellar wind plasma produces free-free continuum emission at mm- to cm-wavelengths, but at flux levels which are observationally challenging [Mullan *et al.*, 1992]. The expected flux density from a mass-losing main sequence star at 10 parsecs ( $1 \text{ pc} = 2 \times 10^5 \text{ AU}$ , the

Earth-Sun distance) is only  $60 \mu\text{Jy}$  ( $1 \text{ Jy} = 10^{-23} \text{ ergs sec}^{-1} \text{ cm}^{-2} \text{ Hz}^{-1} \text{ sr}^{-1}$ ). Wind emission at mm and longer wavelengths will have a characteristic power-law energy spectrum with index  $2/3$  [Panagia and Felli, 1975; Wright and Barlow, 1975; van den Oord and Doyle, 1997]. While wind emission is more intense at millimeter wavelengths the signal must compete with higher sky noise and at present, observations at cm wavelengths with the VLA are the most promising. Limits to mass loss have already been established for more massive A and F stars [Brown et al., 1990] and active, lower mass M stars [Lim and White, 1996; van den Oord and Doyle, 1997]. Microwave emission detected from very young (less than 100 Myr) solar-mass stars is thought to be coronal gyrosynchrotron radiation [Gary and Linsky, 1981; Güdel et al., 1995]. Searches for emission from slightly older stars where this emission will be much less have been unsuccessful or ambiguous [Bowers and Kundu, 1981; Gary and Linsky, 1981; Whitmire et al., 1995; Güdel et al., 1995]. Güdel et al. (1998), obtaining the most sensitive observations prior to this work, placed limits on the flux (and thus mass loss) from three young solar-type stars.

## Observations

We have obtained still more sensitive observations at 3.6 cm (X-band) of the solar analog  $\pi^{01}$  UMa, 14.3 pc distant, with the Very Large Array (VLA) in Socorro, New Mexico. This star was one of the three previously observed by Güdel and is one of a sample of nearby young solar-mass stars selected on the basis of its analogy to the Sun during the Hadean eon (3.8-4.5 Ga) [Gaidos, 1998]. Two tracks of the star were obtained on February 14 and 15 with the array in its C/D (compact) configuration using 27 antennae for a total on-source integration time of 12.2 hours. We believe these are the most sensitive observations obtained to date of a main-sequence star other than the Sun. Simultaneous observations were made of bright point sources for phase and flux calibration when combining the signal from the individual antennae. The data were reduced using the Astronomical Image Processing System (AIPS) software package. The combined map has a resolution of  $7.9 \times 5.1$  arc-seconds and a  $1\sigma$  noise level  $6.4 \mu\text{Jy}$ .

## Results and Discussion

No source was detected at the location of  $\pi^{01}$  UMa (SIMBAD ICRS 2000 coordinates). A  $40 \mu\text{Jy}$  source was detected 15 arc-seconds to the southeast. The offset

of this source from the star was confirmed by measuring its separation from an emission-line galaxy with both optical and radio positions. A plausible counterpart is the nearby binary system of low-mass stars HU 628BC [Al-Shukri *et al.*, 1996]. A possible source 1-2.5 arc-seconds to the NE of the star appears at the  $2\sigma$  level ( $12 \mu\text{Jy}$ ) in the February observations but at the  $5\sigma$  level ( $40 \mu\text{Jy}$ ) in previous VLA observations (Güdel, private communication). The offset is significant and we have no reason to believe the radio source is associated with the star. Even if it is, any variable component is due to flaring and we place an upper limit of  $12 \mu\text{Jy}$  on the total flux density from a wind.

A spherically symmetric stellar wind with density falling as  $r^{-2}$  from a star at a distance  $d$  losing mass at a rate  $\dot{M}_{-10}$  (units of  $10^{-10} M_{\odot} \text{yr}^{-1}$ ) will have the flux density spectrum [Wright and Barlow, 1975; Panagia and Felli, 1975]

$$S_w = 60 (M_{-10})^{\frac{4}{3}} \left( \frac{\lambda}{36 \text{ mm}} \right)^{-\frac{2}{3}} \left( \frac{d}{10 \text{ pc}} \right)^{-2} \mu\text{Jy}. \quad (1)$$

The quiescent emission from the star's 20,000 K chromosphere (optically thick at these wavelengths) is small, roughly  $0.3 \mu\text{Jy}$ . Flaring activity may roughly double this contribution. Correcting for this amount, our detection limit corresponds to a mass loss of  $4 - 5 \times 10^{-11} M_{\odot} \text{yr}^{-1}$ .

Angular momentum, as well as mass, is lost through an ionized, magnetized stellar wind, linking the spin-down of the rotation rate  $\Omega$  with the mass loss,

$$\frac{\dot{\Omega}}{\Omega} \sim \frac{\dot{M}}{M} \left( \frac{R_A}{R_{\odot}} \right)^m, \quad (2)$$

where  $R_A$  is the Alfvén (sonic) radius and  $m$  is a between 0 and 1 depending on magnetic field geometry [Weber and Davis, 1967; Stepień, 1988]. At the Alfvén radius,  $u\dot{M} = B_r^2 R_A^2$ , where  $B_r$  is the radial magnetic field and  $u$  is the solar wind velocity. In a multipole field, small changes in distance can compensate for large changes in  $u\dot{M}$ , thus  $R_A$  will vary only slightly over the history of the Sun. Then,  $M \sim \Omega^{\alpha}$ , where  $\alpha < 1$ . The rotation rates of stars grossly exhibit a power law decay  $\Omega \sim t^{-1/2}$  [Skumanich, 1972], hence the mass evolution will exhibit a power-law behavior as well. Mass loss will decrease inversely with time and the constant is set by the total mass loss and the earliest time at which the rotation-age relation holds (a few 10's of Myr, or when the rotation period was  $\sim 2$  days). Mass loss evolution for 3% and 7% are plotted in Fig. 1 with the

new constraint for  $\pi^{01}$  UMa, previous upper limits for two other (older) solar analogs [Güdel *et al.*, 1998], and the mass-loss of the modern Sun. We are able to rule out mass loss greater than 6% in the context of this model. This observation suggests that mass loss cannot solve the faint young Sun problem for Mars, although the mass loss needed for a temperate early Earth is not yet ruled out. The mass loss of the Sun, extrapolated with the model to an age of 300 Myr, is only  $3 \times 10^{-13} M_{\odot} \text{yr}^{-1}$ . Observations by an upgraded VLA ([www.nrao.edu/vla/html/Upgrade/Upgrade\\_home.shtml](http://www.nrao.edu/vla/html/Upgrade/Upgrade_home.shtml)) or the proposed Atacama Large Millimeter Array (ALMA) [Wootten and Yun 1999] will be unable to detect this amount, but will be able to rule out any mass loss rates significant to the climate of the early Earth.

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**Figure 1.** Mass-loss vs. time in a power-law model for 3% and 7% total mass loss. The first case is required for liquid water on early Mars, the second is the limit to avoid a runaway greenhouse on Earth [Whitmire *et al.*, 1995]. The modern Sun, a new limit from VLA observations of the solar analog  $\pi^{01}$  UMa, and previous limits for two other Sun-like stars are marked. The sensitivity of a single observation by the proposed Atacama array is also noted.

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